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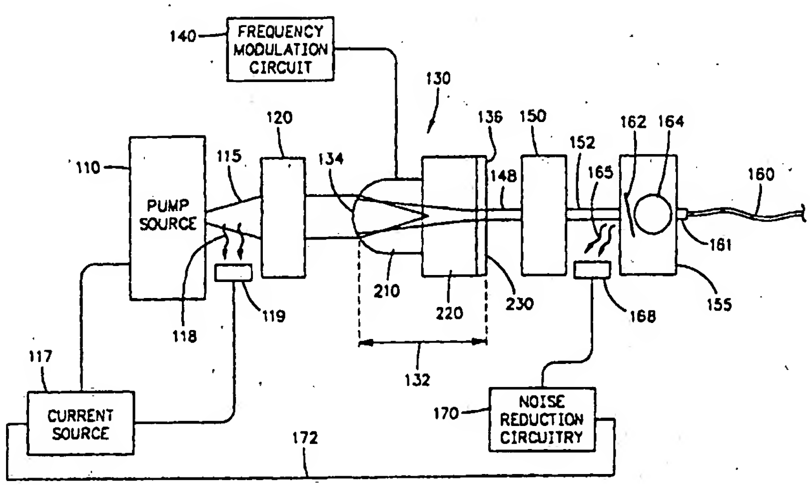

(57) Abstract

A coupled cavity laser provides a single longitudinal mode TEM_{00} output with a narrow linewidth suitable for communications. The coupled cavity laser (130) includes a gain medium (220), a thin etalon (230) that comprises a polarization selective material, end mirrors on opposing ends of the coupled cavity, and a partially reflective interface situated between the end mirrors. The gain medium has a broad gain bandwidth, and the etalon selects a single lasing wavelength from a range of wavelengths. In one embodiment, the gain medium comprises Er, Yb: glass, which has a broad gain bandwidth that includes a range of wavelength from 1530 nm to 1570 nm. The coupled cavity laser may comprise a monolithic laser assembly including an electro-optic modulator element (210), the gain medium, and the etalon. The laser may also include a system that controls the pump source to reduce relative intensity noise (RIN). Furthermore, high output power can be achieved, which advantageously extends the range that an optical fiber can run without requiring a fiber amplifier. The coupled cavity laser is useful for cable TV, dense wavelength division multiplexing ("DWDM"), and satellite communications.

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COUPLED CAVITY LASER SOURCE FOR TELECOMMUNICATIONS

GOVERNMENT RIGHTS

The present invention was made under U.S. Air Force Phillips Laboratory Contract F29601-95-C-0047, U.S. Navy Naval Undersea Warfare Center Division, Newport Contract, N66604-97-M-0207, and U.S. Army CECOM Contract Number DAAB07-97-C-J228, and the U.S. Government has certain rights therein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to lasers, and particularly to lasers that provide a light source for telecommunications systems.

2. Description of Related Art

Computer networks and advanced communications systems of many types have made vast amounts of information widely available. Cable TV, the Internet, telephones, and satellite communications are just a few of the communications systems in use today, and in the future it is almost certain that these communications systems will expand and other types of communications systems will become available. In order to meet the ever-increasing need for expanded communications capacity, telecommunications has become a rapidly growing industry, and is likely to continue to grow in the future.

In general, any communication system requires a way to communicate a message from a transmitter to a receiver. In many instances, cables are used for transmitting a signal. In the past, cable TV systems typically used coaxial cables, but more and more cable TV systems are now installing fiber optic cables in one or more links, and in some locations, all the way to the consumer. Fiber optic cables generally include a bundle of optical fibers, which are flexible waveguides designed to deliver light from a laser source to a light detector.

One large segment of the telecommunications industry–the telephone industry–now almost exclusively uses fiber optic cables to transmit modulated laser signals over long distances. For example, prior to 1983, less than 1% of long distance telephone traffic in the United States was transmitted optically on glass fiber, but by 1990, greater than 90% of long distance telephone traffic traveled over optical fibers.

The cost of installing and maintaining cables is a very significant portion of the overall expense of a communication system. In order to minimize this cost, systems have been developed to increase the transmission capacity of installed cables (i.e., these systems increase "bandwidth"). However, present technology can support modulation only at rates of about 10 Gbit/second per channel due to limitations imposed by external modulators and by opto-electronic receivers. Therefore, in order to take full advantage of installed fiber optic cables, an increase in data rate can best be realized by increasing the number of optical channels simultaneously transmitting information through a single optical fiber. One such type of system under development is a wavelength division multiplexing (WDM) system or a dense wavelength division multiplexing (DWDM) system, in which each separate channel is provided by a slightly different wavelength. The International Telecommunications Union ("ITU") has agreed upon the standard for DWDM to include the range from 1532.68 nm to 1562.23 nm ± 0.4 nm. However, one significant component remains to be developed–a suitable laser source.

A suitable laser source for high bandwidth telecommunications and optical fiber sensor systems would provide (1) high power to overcome losses due to external modulation and to transmit over long distances, (2) wavelength selectability to increase network bandwidth by multiplexing multiple laser sources onto the same optical

fiber, and (3) narrow linewidth to reduce dispersion over long runs of optical fiber.

The conventional light source for optical fiber systems is the laser diode, and specifically the distributed feedback (DFB) laser diode which has the narrow linewidth necessary for communications. However, DFB lasers are limited in power; commercially available high-power DFB lasers provide only 35 mW. Even though higher power DFB lasers are being developed, it is unlikely that commercial units with powers approaching 100 mW will be available in volume, at least for the foreseeable future. Furthermore, like all semiconductor lasers, DFB lasers typically exhibit relative intensity noise (RIN) at frequencies from zero to ten or more gigahertz (GHz), which limits their transmission capacity. Also, the temperature of semiconductor lasers must be carefully controlled to avoid temperature-dependent frequency changes.

The lack of power available from DFB lasers remains a significant problem, particularly for long runs of optical fibers. Optical signals lose power as they travel along an optical fiber; for example, one conventional single mode optical fiber attenuates the signal by about 0.3 dB/km. After a long run of optical fiber, a signal may become so attenuated that it no longer can be received intact. In order to amplify an optical signal before it becomes irrecoverably attenuated, erbium-doped fiber amplifiers (EDFAs) have been developed. EDFAs can be inserted directly into a cable, and are less expensive than the previous alternative of regenerating the signal using a second receiver and transmitter to receive the optical signal, convert it to an electrical signal, and then re-transmit it along an optical fiber. However, EDFAs create noise (and thereby degrade the signal to noise ratio), they are expensive, and it would be a significant advantage if the laser source could provide enough power to reduce or even eliminate the need for EDFAs.

One type of laser that holds promise for telecommunications is a diode-pumped solid-state laser (DPSSL), which includes a solid-state gain medium pumped by optical radiation from a laser diode. DPSSLs only exhibit RIN over a range from zero to tens of megahertz (MHz), making DPSSLs more advantageous than semiconductor lasers from a noise standpoint. DPSSLs have other advantages such as higher power than semiconductor lasers; however, DPSSLs suitable for telecommunications systems have not been available.

For small to moderate levels of optical power, one particularly useful type of DPSSL is a "microlaser", which comprises a short element (i.e. less than about five mm) of solid-state gain medium positioned in a resonant cavity that is defined by two opposing reflective surfaces formed directly on opposing ends of the solid-state gain medium. A pump beam supplied by a semiconductor diode laser pumps the solid-state gain medium to provide energy to support laser operation.

SUMMARY OF THE INVENTION

In order to overcome the limitations of the prior art, a coupled cavity laser is provided that produces a single longitudinal mode TEM_{00} output with a narrow linewidth suitable for communications. The coupled cavity laser includes a gain medium, a thin etalon that comprises a polarization selective material, end mirrors on opposing ends of the coupled cavity, and a partially reflective interface situated between the end mirrors that separates the coupled cavity into a first cavity and a second cavity. The gain medium is situated within the first cavity, and the etalon is situated within the second cavity. In one embodiment, the coupled cavity laser comprises a monolithic laser assembly including an electro-optic modulator element, the gain medium, and the etalon, with the electro-optic element situated within the first cavity, and the gain medium situated between the electro-optic element and the etalon. Advantageously, the electro-optic element can be modulated to "chirp" the laser output by shifting the frequency at a predetermined amount and a constant rate, which is useful to reduce losses in optical fibers. The

laser assembly can be formed as a monolithic structure by, for example, optically contacting the modulator element, the gain medium, and the etalon, which advantageously eliminates air from the laser cavity, encloses all intracavity surfaces, and protects them from contamination by external sources.

In one embodiment, the gain medium comprises Er,Yb: glass, which has a broad gain bandwidth that is dependent upon the loss within the laser cavity. The etalon within the second cavity has a thickness that selects a single lasing wavelength within that gain bandwidth.

Some embodiments include a system that controls the pump source to reduce relative intensity noise (RIN), which is advantageous for communications systems. Extremely low relative intensity noise (RIN) ($<$ 165 dB/Hz at 10 MHz and above) and a narrow linewidth ($<$ 100 kHz, typically $<$ 40 kHz) have been observed. Furthermore, high output power can be achieved; for example some embodiments provide greater than 100 mW of linearly polarized laser light coupled into the optical fiber ($>$ 140 mW uncoupled). It is believed that even higher power levels can be achieved. Advantageously, this high power extends the range that an optical fiber can run without requiring a fiber amplifier. One significant use for the laser source described herein is in telecommunications systems: cable TV, dense wavelength division multiplexing ("DWDM"), and satellite communications. The laser could also be used in other systems that require a single mode, narrow bandwidth laser source.

The single longitudinal mode TEM_{00} output can be readily coupled into a single mode optical fiber. The wavelength produced by one embodiment of the laser, around 1550 nm, is optimal for many currently installed fiber optic systems; and furthermore, the laser source is suitable for DWDM systems because a wavelength can be provided within a range of about 1530 nm to 1570 nm. Furthermore, the wavelengths around 1550 nm are "eye-safe" and therefore suitable for free-space communication systems.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of this invention, reference is now made to the following detailed description of the embodiments as illustrated in the accompanying drawing, wherein:

Fig. 1 is a schematic diagram of a coupled cavity solid state laser apparatus for communications;

Fig. 2 is a graph of noise intensity vs. frequency, illustrating relative intensity noise (RIN) and the effect of a noise reduction circuit to reduce RIN;

Fig. 3 is a block diagram of one embodiment of the noise reduction circuit for reducing RIN;

Fig. 4 is a side view of one embodiment of the laser assembly shown in Fig. 1;

Fig. 5 is an exploded, perspective view of the laser assembly shown in Fig. 4;

Fig. 6 is a flow chart that illustrates steps for making a laser using a silicon base;

Fig. 7 is an exploded view of one embodiment of a telecommunications laser, illustrating a silicon base on which the laser components are mounted, a cooler for cooling the silicon base, and a frame for encasing the base and cooler;

Fig. 8 is a cross-sectional side view of a telecommunications laser implemented on a silicon base;

Fig. 9 is an exploded side view of a telecommunications laser implemented on a silicon base;

Fig. 10 is a top view of a telecommunications laser implemented on a silicon base;

Fig. 11 is an exploded view of a mounting structure, a laser assembly, and a welding strip for mounting the laser assembly on the silicon base;

Fig. 12 is a top view of a mounted laser assembly of Fig. 11; and

Fig. 13 is a diagram of a wavelength division multiplexing (WDM) communication system that utilizes the

communications laser described herein.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

This invention is described in a preferred embodiment in the following description with reference to the Figures, in which like numbers represent the same or similar elements.

For ease of description, the laser may be described herein as a "1550 nm" laser. It should be apparent from the description herein that the laser can operate at one wavelength within a range of wavelengths between about 1530 and 1570 nanometers (nm), and that reference to a "1550 nm laser" is not meant to be limiting to a specific wavelength.

Some optical components are referred to herein as "etalons", which is meant to refer to components that have two opposing flat, parallel surfaces polished to etalon tolerances. For example the parallelism between the flat sides of an etalon should be less than $\lambda/4$, and if possible less than $\lambda/10$. The roughness of the flat surfaces should be less than 10 Å rms in order to facilitate optical contacting with other optical components.

Reference is first made to Fig. 1, which is a schematic diagram of a coupled cavity solid state laser apparatus for communications. The laser is designed to produce a single longitudinal mode TEM_{00} output, which can be easily matched to a single mode fiber. A suitable pump source 110 produces a pump beam 115. The pump source 110 can be any suitable source of optical radiation, and preferably comprises a laser diode. The pump source 110 is controlled by a diode driver 117. A sample 118 of the pump beam 115 is sensed by a photodiode 119. The photodiode may be positioned just off the beam path of the pump beam where it can receive a lower power radiation lobe and thereby sample the pump light. Alternatively, the pump beam may be sampled by sensing backscattered light from the optical elements such as coupling optics 120 or a partial reflector (not shown). The photodiode 119 operates as a light sensor to produce a feedback signal, which is then supplied to the diode driver 117 to adjust the bias current so that the pump source 110 supplies an approximately constant beam power over the expected lifetime of the laser. One advantage of an approximately constant pump power is that thermal flows within the laser cavity remain approximately constant, which permits the laser components to be designed with substantially predictable temperatures and predictable temperature variations, which in turn provides substantially predictable performance over the lifetime of the laser.

The pump beam 115 is applied through suitable coupling optics 120 to a coupled cavity laser assembly, shown generally at 130. In one embodiment, the coupling optics comprise a lens, such as a ball lens that focuses the pump beam into a narrow spot within the laser assembly in such a way as to provide single mode operation.

The laser assembly 130 defines a coupled cavity, illustrated by an arrow 132, defined between a back end 134 and a front end 136. One embodiment of the laser assembly is described with reference to Figs. 4 and 5; generally, the laser assembly includes an electro-optic modulator, a gain medium, and a polarizer connected together to define a coupled cavity. A frequency modulation circuit 140 supplies signals to the electro-optic element, which in response modulates the laser beam's wavelength in a manner suitable for the intended use; for example, in one embodiment the modulation circuit 140 supplies a "chirp"; specifically the modulation circuit 140 shifts the laser's frequency by a relatively small amount (e.g. a few hundred MHz), at a constant rate of about 10 kHz. It has been found that a frequency shift of about 200 MHz to 300 MHz at a constant rate of 10 kHz is useful to compensate for problems that may be caused by stimulated Brillouin scattering (SBS) processes in optical fibers. Other embodiments may require different frequency shifts and/or different rates. In one embodiment, the modulation circuit 140 supplies a user-selected voltage between zero and ten volts to the electro-optic material, which allows the laser's frequency

to be shifted by up to about 40 MHz. In another embodiment the modulation circuit may be used to enhance the phase stability of the laser.

The laser output 148 from the laser assembly 130 is transmitted through an isolator 150 that allows one-way optical transmission, thereby blocking undesirable optical feedback into the optical cavity. The isolated laser output 152 is then coupled through a fiber optic coupler 155 to an optical fiber 160. A ferrule 161 is used to hold the optical fiber in position. In the illustrated embodiment, the coupler 155 comprises a substantially transmissive partial reflector 162 and a ball lens 164, but it should be apparent that other embodiments may utilize other optics. Backscattered light 165 from the partial reflector 162 is detected by a photodiode 168 that provides a feedback signal to a noise reduction circuit 170, which produces a noise reduction control signal on a line 172 that is applied to the diode driver 117. The noise reduction control signal then operates to reduce low frequency (e.g. less than 2 MHz) noise such as relative intensity noise that may result from relaxation oscillations.

Reference is now made to Fig. 2, which is a graph of noise intensity vs. frequency, to illustrate relative intensity noise (RIN) and the effect of the noise reduction circuit 170 to reduce RIN, which is evidenced as frequency-dependent amplitude variations in the laser output at low frequencies (e.g. less than 2 MHz). Relaxation oscillations have been defined as "small-amplitude, quasi-sinusoidal, exponentially damped oscillations about the steady-state amplitude that occur when a continuously operating laser is lightly disturbed," A.E. Siegman, *Lasers*, University Science Books, Mill Valley, CA, Chapter 25, 1986. The nature of certain lasers to exhibit relaxation oscillations is believed to be dependent upon factors such as the fluorescence lifetime of the lasant material, the reflectivity of the end mirrors, and cavity losses. The relaxation oscillation phenomena increases RIN.

Like many noise processes, RIN degrades communication at the frequencies where it appears. Specifically, the effect of RIN is to reduce the maximum signal-to-noise ratio, increase bit-error rates (for digital communications), and reduce the maximum achievable transmission rate. Of course RIN is only one noise process; other noise processes can also adversely affect communications.

Fig. 2 shows a graph 180 typical of free-running (i.e. uncompensated) RIN (measured in dB) as a function of frequency for one embodiment of the diode-pumped solid state laser described herein. Apart from the very low frequencies (e.g. below 20 kHz) which are generally not of interest, RIN increases with frequency to a maximum frequency (f_{max}) typically between 500 kHz and 1 MHz. At higher frequencies, RIN decreases sharply until f_{limit} (several MHz), where it approaches the shot-noise limit. At high frequencies (e.g. above several MHz) RIN is essentially shot noise limited (< 170 dB/Hz). The free-running peak RIN frequency and corresponding peak RIN amplitude vary from laser to laser, but these values are generally in the region of 500 kHz to 1 MHz and -85 dB/Hz to -97 dB/Hz. At low frequencies, RIN follows a 1/f dependency, and at 20 kHz, RIN is typically < 120 dB/Hz.

Semiconductor lasers are also affected by RIN. For such semiconductor lasers, the peak RIN is typically much higher–in the GHz range (e.g. one GHz)–and as a result, communication systems that use semiconductor lasers as a light source are adversely impacted by RIN over a very broad range of frequencies. Therefore, semiconductor lasers have a substantial inherent disadvantage when compared with solid-state lasers, which in comparison exhibit substantial RIN only over a few MHz.

In order to reduce RIN, the noise reduction circuit 170 produces a noise reduction control signal that is applied to the diode driver 117 in order to reduce relative intensity noise (RIN) from relaxation oscillations. Such noise reduction systems are known and disclosed, for example, in a publication by Thomas J. Kane, *Intensity Noise in Diode-Pumped Single-Frequency Nd:YAG Lasers and its Control by Electronic Feedback*, IEEE Photonics Technology Letters, Vol. 2, No. 4, April 1990, pp. 23-24, and in U.S. Patents 5,177,755 and 5,253,267, both of which are

entitled *Laser Multiple Feedback Control Circuit and Method*, by Keith Johnson. Noise reduction systems are also shown in the following publications: De Geronimo et al., *Optoelectronic feedback control for intensity noise suppression in a codoped erbium-ytterbium glass laser*, Electron. Lett., 1997, Vol. 33, No. 15, pp. 1336-1337, and Taccheo et al., *Intensity noise reduction in a single-frequency ytterbium-codoped erbium laser*, Opt. Lett., 1996, Vol. 21, pp. 1747-1749. In general, these publications disclose a system where the intensity of the laser output is monitored over time and used as feedback to actively control the current to the laser diode, which has the effect of modulating the pump beam to cancel out RIN.

The noise reduction circuit 170 comprises any suitable circuit that functions to phase shift the laser's amplitude fluctuations, and amplifies the signal as appropriate to approximately cancel out RIN from the particular laser system. In general the gain of the circuit 170 at the maximum RIN frequency is set to a value that just compensates for RIN at the maximum RIN frequency (i.e. reduces RIN by the maximum amount). This gain value and the maximum RIN frequency may be determined in the factory on an individual basis for each laser and then set accordingly. Alternatively, an approximate gain value and/or an approximate maximum RIN frequency may be pre-determined and built into each laser. Still other alternatives may include active electrical systems that monitor the RIN frequency and automatically adjust the gain value accordingly. At other frequencies of interest that may be affected by RIN, the circuit is designed so that the gain of the noise reduction circuit varies with frequency.

Reference is now made to Fig. 3, which is a block diagram of one embodiment of the noise reduction circuit 170. The signal from the photodiode 168 is first amplified in an amplifier 190 that two stages including a first differentiator 192 that increases signal gain (voltage) with increasing frequency by a predictable amount of +6 dB/octave (+6 dB is a doubling of voltage, one octave is a doubling of frequency), which operates to cancel out the naturally declining -6 dB/octave response of the particular laser at higher frequencies. The second stage of the amplifier amplifies the signal by an additional +6 dB/octave around the maximum RIN frequency (e.g. 500 kHz to 1000 kHz). Next, a limiter 194 operates to reduce the amplified signal gain if it exceeds a predetermined limit, which enhances the stability of the noise reduction process. Next, a phase shifter 195 changes the phase of the amplified signal by an amount necessary to cancel the RIN. In one embodiment, the signal from the photodiode 168 has already been shifted by 90°, and therefore the phase shifter reverses it by 270° to provide a net 180° out-of-phase waveform. The phase shifter 195 may be adjustable in order to provide a more precise null (i.e. more precise cancellation of the noise).

Next, a variable gain amplifier 196 provides for fine tuning of the overall circuit gain in order to achieve maximum noise reduction, while maintaining a margin of stability. A resultant feedback signal 197 is supplied to the diode driver 117 where it is summed with the bias value for the DC diode current, and then the appropriate drive current is applied to the laser diode to drive and modulate the laser diode output to cancel the unwanted system resonance. The graph line 185 in Fig. 2 shows an observed result of the noise reduction system, in which the peak has been substantially flattened and RIN has been substantially lowered at all frequencies around f_{max}. In one embodiment, the maximum RIN has been typically reduced by 20 dB or more, and often 25-34 dB reductions are observed.

Reference is now made to Figs. 4 and 5, in conjunction with Fig. 1. Fig. 4 is a side view of one embodiment of the laser assembly 130 shown in Fig. 1, and Fig. 5 is an exploded, perspective view of the laser assembly. Generally, the laser assembly 130 includes an electro-optic material 210 (sometimes called a "Pockels cell"), a gain medium 220, and a polarization-selective etalon ("polarizer") 230 that has smooth parallel sides. The elements of the laser assembly 130 are coupled together by optical contact or other suitable method to form a monolithic structure

that advantageously eliminates air from the laser cavity and protects the intra-cavity surfaces from external contamination, resulting in greater stability of laser operation over a wide range of temperatures, pressures, and humidities. The roughness of all flat surfaces on the optical elements should be less than 10 Å rms in order to facilitate optical contacting with other optical components. In the following discussion, reference may be made to the x-, y-, and z- axes. The x-y-z axes are defined by the laser axis; the z-axis is aligned with the center of the laser beam, and the x and y axes are perpendicular to the z-axis as illustrated in Fig. 5.

The electro-optic material 210 has a spherical curve on the back end 134, and opposite thereto a flat surface 212. The back end 134 is coated for high reflection (e.g. > 99.9%) at 1550 nm and for antireflection at the pump wavelength (e.g. 975 nm). The flat surface 212 may remain uncoated, or it may be coated for anti-reflection at 1550 and the pump wavelength. The spherical curve (e.g. about 50 mm) enhances stability of the cavity's laser modes, and also provides focusing power for the pump beam. On its other end, the electro-optic material has a rectangular cross-section. The electro-optic material preferably includes ($LiNbO_3$), but other electro-optic materials such as potassium dihydrogen phosphate (KDP) or ammonium dihydrogen phosphate (ADP) could be used as alternatives. The frequency modulation circuit 140 is electrically coupled to the frequency modulation circuit by a pair of electrodes 235 positioned on opposites side of the electro-optic material, which allow a voltage to be asserted across the electro-optic material. The electrodes 235 may comprise metallized contacts formed on the sides of the electro-optic material; alternatively silver or gold epoxy, for example could be used to provide a conductive surface.

The gain medium has the form of a block with two flat opposing surfaces including a back side 222 and front side 224 that are parallel to each other. The gain medium in this embodiment a square cross section, and the front side 224 has a bevel 226 around its sides. In the preferred embodiment the gain medium 220 comprises erbium co-doped with ytterbium in a phosphate glass host material ("Er,Yb: glass") available from Kigre, Inc. of Hilton Head, South Carolina. In operation, the ytterbium ions efficiently absorb energy from the pump radiation at 980 nm, and then transfer the absorbed energy to the erbium ions to create a population inversion, which allows lasing operation to begin. The erbium system has three energy levels relevant to laser operation, with the terminal state of the lasing transition lying near the ground state which makes the terminal state population of erbium sensitive to the temperature of the glass medium. The Er,Yb: glass comprises a suitable concentration of erbium and ytterbium, which may vary between designs. For example Taccheo et al., *Widely Tunable Single Frequency Erbium-Ytterbium Phosphate Glass Laser*, Appl. Phys. Lett. 68 (19), May 6, 1996, pp. 2621-2623, discloses a Er,Yb: glass laser with an erbium concentration of 1×10^{20} ions/cm^3 and a ytterbium concentration of 2×10^{21} ions/cm^3. U.S. Patent No. 5,225,925 discloses a variety of concentrations and proportions, such as a proportion of ytterbium ions to erbium ions in a range between 4:1 and 20:1, for example. Alternatively, other co-doped materials could be used, such as those described in U.S. Patent No. 4,701,928, entitled "Diode Laser Pumped Co-Doped Laser," by Fan et al. In other alternatives, any other suitable solid state materials, glass or crystal, may be used. Such alternatives may be suitable if they have a broad gain bandwidth, which is defined herein as about 5 nm or greater.

The gain medium has a characteristic gain bandwidth, which defines a range of wavelengths within which it can lase. The Yb,Er: glass gain medium has a much broader gain bandwidth than typical crystalline microlaser gain media, which advantageously allows operation over a wide range of wavelengths. Specifically, for Er,Yb: glass, a range between about 1532 nm and 1567 nm (about 35 nm) can be obtained. As disclosed in Taccheo et al., *Widely Tunable Single Frequency Erbium-Ytterbium Phosphate Glass Laser*, Appl. Phys. Lett. 68 (19), May 6, 1996, pp. 2621-2623, the gain bandwidth of Er,Yb: glass varies dependent upon the losses in the cavity, and by varying the

reflectivity of the output coupler, several ranges of wavelengths can be obtained.

The broad bandwidth of Er,Yb: glass precludes use of a conventional approach to single-mode cavity design, which would be to design the cavity with an optical path length small enough that the free spectral range (FSR) of the laser cavity will be larger than the linewidth of the gain medium, which allows no more than one mode at any given time to experience gain above half of the maximum. For many rare-earth transitions in crystalline media, conventional non-coupled cavity approaches would dictate an optical path length of at least several hundred microns (e.g. 500 microns), but for Er,Yb: glass, which has a broad bandwidth, conventional non-coupled cavity designs would require an optical path length so small (e.g. about 35 microns), that sufficient gain would not be available for laser operation. In order to overcome this problem and still provide single mode operation, a coupled cavity configuration is utilized.

A coupled cavity configuration, defined within the main laser cavity 132, includes a first cavity 260 defined between opposite ends of the electro-optic material and the gain medium, and a second cavity 270 defined between opposite sides of the polarizer 230 (i.e. the thickness of the polarizer determines the dimensions of the second cavity). The interface between the first and second cavities comprises a partially reflective coating 275 that provides mode selection via coupled cavity effects.

In one embodiment, by using the polarizing etalon to select a single wavelength, and providing the appropriate reflectivity on the output coupler to select a predetermined cavity loss lasing operation can be achieved at any wavelength within the range of about 1530 to about 1570. The etalon may be formed with a predetermined thickness within a range of 80 to 120 microns, and preferably about 100 microns. The ability to utilize a single manufacturing process to produce lasers with different wavelengths is advantageous to produce cost-effective lasers for communications systems such as dense wavelength division multiplexing ("DWDM") systems, in which multiple beams, each having a separate wavelength, are modulated separately, and then multiplexed together and transmitted simultaneously along an optical fiber.

It has been found that a reflectance of about 20% is effective; however, it is believed that other reflectivities (e.g. between about 15% and 25%) may provide suitable performance in some embodiments. The partially reflective coating 275 defines the separation between a first cavity shown at 260 and a second cavity shown at 270, all within the main laser cavity 132.

In order to provide a back mirror on the back end, the electro-optic material is coated with a first optical coating 280, which has a high reflectance (e.g. 99.9% or more) at the lasing frequency in order to promote lasing operation. The first coating is also coated for anti-reflection at the pump frequency, in order to allow passage of the pump beam. An output mirror is provided on the front end 136 by coating the polarizer with a second coating 282 that is substantially reflective at the lasing frequency. In one embodiment the reflectivity of the second coating 282 is about 97%; however, the reflectivity of the second coating 282 may be varied to obtain different lasing wavelengths. Depending upon the embodiment, the second coating may be reflective or transmissive at the pump frequency. The interface between the electro-optic material and the gain medium may remain uncoated, or may be coated with a coating 290 for low absorption and/or antireflection.

The polarizer has the form of a thin (e.g. about 100 microns) etalon with two flat opposing parallel polished surfaces including a back side 232 and the front end 136. The parallelism between the flat sides of an etalon should be less than $\lambda/4$, and if possible less than $\lambda/10$. In the embodiment shown in Figs. 4 and 5 the polarizer has a square cross section (e.g. 2 mm), alternatively other cross-sectional shapes, such as circular, can be used. In one embodiment the polarizer 230 is oriented to so that the E-field parallel to the y-axis is transmitted. The polarizer 230

performs multiple functions: in addition to defining the second of two cavities in the coupled cavity configuration, the polarizer also functions to restrict laser operation to one polarization. Polarized emission is required by the external (i.e. outside the cavity) modulators currently used in communication systems. In one embodiment the polarizer comprises a polarization selective material such as Polarcor™ optical material, which is type of polarizing glass available from Corning Incorporated, Corning, New York 14831. Polarcor™ is a broad bandwidth, high transmission, dichroic glass polarizing material made of borosilicate glass with aligned silver particles, having an index of refraction of $n = 1.510$ at 1550 nm, and an extinction ratio greater than 10,000:1. Alternatively, other suitable polarizers may be used.

The polarizer 230 has a thickness that is relatively thin (e.g. less than about 200 microns and preferably about 100 microns). In embodiments that utilize Polarcor™, which is presently available only in a 200 micron thickness, the thickness is reduced and both sides are polished. In alternative embodiments, other polarization selective materials may be used, such as a thin (e.g. $<$ 100 micron) etalon of silicon where polarization selectivity is achieved by thinly etched diamond-turned parallel lines along one eigen-axis of the silicon crystal. One advantage of use of silicon is that the resulting Fresnel reflection at the interface between the polarizer and the gain material could be sufficient to provide the intra-cavity reflection required for the coupled cavity laser, without requiring the partially reflective coating 275. In alternative embodiments that do not require a polarized output, the polarizer can be replaced with any suitable optical material, such as optical glass or sapphire, which could provide more effective heat transfer.

Generally, the coupled cavity laser described herein may be implemented in a variety of ways. One implementation is described in Ser. No. 08/988,947, entitled "Laser Assembly Platform with Silicon Base" filed December 11, 1997, assigned to the same assignee, and hereby incorporated by reference herein. The following specifically describes one such assembly process and platform in which the elements of the telecommunications laser are mounted on a silicon optical bench (or "base"). This process can provide a low cost, reliable method for manufacturing the telecommunications laser described herein; alternatively, conventional processes could be used.

Generally, the silicon base begins as a monolithic structure that is precisely formed with features for affixing the various laser components. The same or additional features may also clearly define the position of the laser components to within very close tolerances. Silicon is an advantageous material for the base for any of a number of reasons: it is readily available, it has good thermal conductivity and it has a low coefficient of thermal expansion. Silicon in a single-crystal form is particularly useful, although polycrystalline silicon could be used for some applications, as could other materials with similar characteristics. Use of a single-crystal monolithic silicon base for all of the laser components that require alignment has a number of advantages: one advantage is that all the laser components can be easily situated within close tolerances, which is very useful for the final alignment step, and another advantage is that a single TE cooler can be used, which simplifies design and reduces cost. However, the advantages of silicon are complicated by the fact that the materials that are typically used to hold and support optical components, such as copper, generally cannot be directly connected to silicon.

Reference is first made to Fig. 6, which is a flow chart that generally illustrates the process for making a laser assembly using a silicon base. A first step 310 is providing a silicon blank, which can be a monolithic, single-crystal piece, and forming the desired features thereon. Generally, one surface of the silicon blank can be taken as the reference plane, and the other surfaces are formed in a predetermined relationship with the reference plane, such as parallel or perpendicular. The well-defined crystal axes of single-crystal silicon permit etching as a means for forming very precise features that can be used to simplify alignment of the laser elements during subsequent

assembly. Also, etching techniques, such as chemical etching, are well known in the semiconductor industry and provide a very precise and reproducible method for forming the desired features on the silicon base. Advantageously, etching techniques provide a way to produce large quantities of precise, uniformly formed silicon bases at low cost. Alternatively, the silicon base can be precision machined using diamond turning techniques to form the desired features.

At step 320, one or more of the predetermined silicon surfaces on which attachment of the laser elements is to occur are first plated with a suitable material such as nickel followed by gold ("nickel-gold"). The plated surfaces are then pre-tinned at the locations on the silicon where soldering is desired.

Next, at step 330, welding strips are soldered to the plated, pre-tinned surfaces of the silicon platform at predetermined locations, using any suitable solder such as, for example, Sn/Pb/Cd solder having ratios of 51.2/30.6/18.2, which has a melting point of about 145°C. The welding strips are positioned appropriately, and then soldered to the silicon platform in order to provide a suitable surface for welding components thereto. The welding strips may comprise a material such as kovar that is suitable for soldering to a plated and pre-tinned silicon surface. Advantageously, kovar has a small coefficient of thermal expansion (about 5×10^{-6} m/°C.) similar to that of silicon (about 4.6×10^{-6} m/°C.). Also, kovar has good thermal conductivity (about 14.2 W/m/°C). Additionally, kovar has good absorption characteristics at a wavelength of 1.06 microns–the typical wavelength of commercially available Nd:YAG welding lasers–which means that kovar is well suited for laser spot welding. For example, about 7.0 Joules is needed to spot weld a lap joint of 0.3 mm kovar, and about 4.0 Joules is needed for a filet joint. Furthermore, kovar is relatively easy to machine in comparison with invar. However, other materials may be used as the welding strips.

Next, at step 340, a laser component is placed in its exact desired position, which may require optical alignment using a small HeNe laser, for example. Once in position, the component may be clamped to hold it during the welding steps. Next, at step 350, the component is spot-welded to the welding strip using a bracket or other suitable connecting device. Spot-welding is performed using a laser with a wavelength, power, and beam size suitable for welding the component and welding strip together, such as a high power pulsed Nd:YAG laser. For each of the laser components, the positioning and welding steps are repeated. Advantageously, such a welding technique provides a quick and permanent connection. Laser welding is a particularly useful manufacturing technique for all components that require alignment.

Sometimes it may be preferable to connect components directly to the unplated silicon. For example, a thermistor may connected directly to the base in order to continuously monitor its temperature. To attach components directly to the silicon, a one-part thermal epoxy, such as available from Epoxy Technology of Billerica, MA, can be used. Such an epoxy will not outgas until 300° C and 10^{-7} torr; however, curing the epoxy requires heating to high levels (e.g. 85° C. for twelve hours). Alternatively, a soldering process may be used for some materials; for example, aluminum nitride can be soldered directly to silicon that has been plated and pre-tinned.

Reference is now made to Fig. 7, which is an exploded view of one embodiment of an implemented telecommunications laser. A silicon base 400 is shown having features formed thereon for positioning and connecting laser components, these features including a flat diode platform 410, a flat optics platform 420 formed below the diode platform, a vertical abutment 430, and a flat output coupler platform 440. In preparation for the assembly process, certain surfaces have been plated and pre-tinned, including a pair of surfaces 412 on the diode platform 410, a surface 422 on the optics platform 422, a surface 442 on the output coupler platform 440, and the underside of the silicon base. The silicon base 400 is connected on its underside to a conventional thermoelectric

("TE") cooler 450, which is utilized to control the temperature of the silicon base by maintaining it at a constant temperature. The "cool" side 452 of the TE cooler is attached to the plated and pre-tinned underside of the silicon base, by for example soldering. The opposite (i.e. "hot") side of the TE cooler 92 is connected onto a suitable frame 460 by any suitable means such as soldering. The frame 460 acts as a heat sink for the TE cooler, and also can provide support for electrical connections to and from the laser components through, for example, a hole 462 formed on one side of the frame. A second hole 464 may allow the optical fiber to pass through. After providing for passage of appropriate cables, the holes 462 and 464 can by sealed by any appropriate means, and the frame 460 can sealed with a cover 466 and held in place by screws 468 to prevent contamination of the optical components by external sources such as dust.

Referring now to Figs. 8, 9, and 10, a more detailed description of the laser assembly and their manufacture will be provided. Figs. 8, 9, and 10 respectively show a cross-sectional side view, an exploded side view and a top view of the telecommunications laser implemented on the silicon base 400. As discussed for example with reference to Fig. 1, the components assembled on the base include the pump source 110, the photodiode 119, the coupling optics 120, the laser assembly 130, the optical isolator 150, the fiber optic coupler 155 and the photodiode 168.

Alternatively, one or more additional optical components, such as an optical modulator shown in Fig. 13 may be mounted on the base. For example, an optical modulator may be situated between the isolator 150 and the coupler 155.

A laser diode assembly 500, including a laser diode chip 502 and a metal block 504 that may be formed of copper, is mounted on the diode platform 410. The laser diode chip 502 comprises any suitable laser diode as long as it provides the desired output characteristics such as wavelength and power. In one embodiment, a conventional broad area laser diode for optical pumping at an appropriate wavelength is used, for example at 980 nm. Alternatively, a laser diode bar or an array of laser diodes may be used in place of a broad area laser diode.

To affix the laser diode assembly 500 in position, a pair of welding bars 510 are first soldered in predetermined positions to the plated, pre-tinned diode platform 410. The laser diode assembly 500 is then situated between the two welding bars 510, which aid in roughly positioning the laser diode assembly. In order to more effectively conduct heat from the laser diode into the base, a suitable foil such as an indium foil (not shown) can be placed between the laser diode assembly and the base.

An alignment step may be utilized to align the emitter of the laser diode in its desired position on the base, using any appropriate technique, and once the laser diode is properly aligned, the laser diode assembly is clamped in position for welding. To couple the laser diode assembly to the welding bars, a pair of L-shaped brackets 512 are positioned so that one side of the "L" contacts the welding bar and the other side contacts the laser diode assembly and then spot-welded using a laser welding process in which a high energy beam of laser radiation is directed at the spot to be welded. The welding spots are indicated by dark spots in Fig. 10. In one embodiment, the L-shaped brackets 512 are formed of kovar which can be readily welded to the kovar welding bars 510.

The coupling optics 120 include a ball lens 520 to focus optical radiation from the laser diode 502 into a focal point within the gain medium of the laser assembly 130, thereby providing high intensity optical radiation to pump the gain medium. The ball lens may be antireflection coated. Alternatively, other types of known focusing optics can by used or the coupling lens may be omitted. For example the laser diode may be situated sufficiently close to directly pump the gain medium without the need to focus the pump radiation, a configuration commonly termed "close-coupled".

The ball lens 520 is situated in a lens holder 522 which may be a metal cylinder. The lens holder 522 is placed on the silicon base in a predetermined location, and may be aligned using a HeNe alignment beam. Alternatively, silicon etching techniques could be used to provide precisely positioned alignment marks and/or ridges on silicon base to align the lens holder reliably and quickly. A single welding pad 524 formed of kovar is connected to the optics platform 420. A U-shaped clip 526 or other suitable structure, also formed of kovar, includes two legs that straddle the lens holder 522 and hold it in position. The two legs of the U-shaped clip 526 are then spot welded to the welding pad 524.

Referring now to Figs. 11 and 12 in conjunction with Figs. 8, 9, and 10, a further description of the laser unit 130 and its assembly will be provided. Fig. 11 is an exploded view of components for mounting the laser assembly 130 on the silicon base, and Fig. 12 is a top view of a mounted laser assembly. In the embodiment described elsewhere with reference to Figs. 4 and 5, the laser assembly 130 includes the electro-optic modulator 210, the gain medium 220, and the polarizer 230, all coupled together by optical contact, for example. A laser cavity is defined by optical coatings formed on opposing ends 134 and 136 of the laser unit 130. Such a laser cavity may define a flat-flat configuration, a curved-flat configuration, or any other suitable laser cavity configuration. Other embodiments could include one or more optical elements affixed to the solid state gain medium, such as a heat spreader.

A mounting structure, shown generally at 529, includes two mounting arms 530 and 531 on which a pair of electrodes 533 have been formed. The mounting arms 530 and 531 define a center opening 536, and the electro-optic material 210 has a shape that fits within this opening. As illustrated in Fig. 12, which is a top view of the laser assembly assembled to the mounting arms, the back side of the gain medium 220 includes surfaces 538 extending outwardly from the boundaries of the electro-optic unit. These surfaces 538 directly abut the mounting arms with the electro-optic material situated between the mounting arms. Advantageously, the abutting relationship between the gain material and the mounting arms provides a thermal path for heat flow from the gain material, through the mounting structure 529, and to the silicon base 400. The laser assembly 130 may be soldered to the mounting arms by, for example a gold solder. One advantage of using a metal solder is that it provides a conductive path from the electrodes 533 to the electro-optic material. Alternatively any suitable method, such as thermal epoxy, may be used.

The mounting structure 529 is affixed to the silicon base 400 in a position so that the laser unit can be optically pumped by pump radiation from the laser diode 502. The silicon base has a vertical face 532 formed in the abutment 430 at a predetermined distance from the ball lens 520. The mounting structure 529 has a vertical surface 534 formed below the mounting arms, which abuts against the face 532 on the abutment. The mounting arms may also rest partly on the optics platform 420. As a result, the laser unit 130 can be positioned approximately within the proper z-plane (i.e. along the lasing axis). Also, the interface between the face 532 and the surface 534 may have a close, thermal contact, in order to conduct heat from the laser unit 130 into the silicon base 400, where it can be dissipated. Thermal conductivity between adjacent surfaces may be enhanced by use of heat conductive materials such as indium foil or thermal epoxy.

To affix the mounting arms to the base, a welding strip 540 is first soldered across the bottom of both of the mounting arms. A pair of L-shaped brackets 542 (Figs. 5 and 6) are then used to permanently affix the mounting arms by spot-welding. Before welding, the laser unit 130 may be aligned to the proper x-y coordinates by any suitable method such as using a HeNe laser.

In some circumstances, it is desirable to electrically isolate the laser unit 130 from the conductive silicon base 400 while still providing a path for heat to flow from the solid state laser unit to the base. In one such

embodiment the mounting arms that connects the laser unit with the silicon base may comprise aluminum nitride ("AlN"). The electrodes 533 formed on the mounting arms may then be used to deliver the required drive voltage/current to the electro-optic modulator of the laser unit with the necessary bandwidth. Alternatively, the modulator may be electrically coupled via a wire or any other suitable method. Advantageously, AlN can be spot-welded to kovar using a high power laser by first metallizing predetermined locations to provide soldering pads, which can then be soldered to kovar brackets, which in turn can be laser welded to kovar welding strips on the base. Furthermore, AlN has a coefficient of thermal expansion very close to that of silicon, it has high thermal conductivity (170 W/m/°C), and it has a low thermal expansion coefficient (4.6 x 10^{-6} m/°C). However, alternative materials can be used, and it would be advantageous if the alternative material is thermally conductive and has a thermal expansion coefficient approximately equal to the thermal expansion coefficient of silicon.

Referring again to Figs. 1, 8, 9, and 10, an output assembly 600 includes a cylindrical metal housing 605 for the optical isolator 150, a partial reflector 162, a fiber coupling lens 164, a fiber-ferrule 161, and an optical fiber 160. The housing 605 can be machined from stainless steel with an appropriate shape to accommodate the elements that fit within it. A hole 607 is provided in the housing in a position to allow light reflected from the partial reflector 162 to be detected by the photodetector 168.

To connect the laser output assembly 600 to the base 400, a kovar welding pad 610 is soldered to the output coupler platform 440. The laser output assembly 600 is then placed in its preliminary position and aligned. Next, a U-shaped kovar bracket 612 is put in position over the laser output assembly and the bracket 612 is spot-welded to the kovar welding pad 610.

In this embodiment, it may be desirable to maintain the laser diode assembly 500 and the laser unit 130 at different, optimal temperatures, even though both components are connected to the same base. We have found that the single base can still allow for thermal differences between optical components by proper selection of the temperature of the base 400 (the "base temperature") and proper selection and control of the drive current applied to the laser diode 502. Because the heat generated in the laser diode is a function of the drive current; therefore its temperature is approximately a function of the drive current and the temperature of the silicon base 400. Also, the temperature of the laser assembly 130 is approximately a function of the pump power received from the laser diode and the temperature of the silicon base. Thus, the pump power and the base temperature can be considered as the two variables in two simultaneous equations that determine the temperatures of the laser diode and the laser element. The thermal resistance between the laser diode assembly 500, the laser assembly 130 and the base 400 can be considered to be approximately constant. Therefore, by monitoring the output of the laser assembly while varying the base temperature and the pump power, the base temperature and the pump power for optimizing the desired laser output of the laser assembly can be determined. Then, the optimized laser output can be maintained by using feedback and control techniques for the temperature of the silicon base and the optical pump power.

Referring again to Fig. 7, the base temperature can be maintained and controlled by, for example, controlling the single TE cooler 450 by any suitable means. In order to monitor the temperature of the silicon base, a temperature sensor such as a thermistor 620 may be mounted in a hole 622 in the silicon base,, which provides a signal on a connection 624 to a controller 626, such as a microprocessor, which controls the TE cooler over a connection 630. The controller can thereby monitor and control the temperature of the base 400. To monitor the optical pump power, the photodetector 119 (Fig. 1) is situated to detect a portion of the optical pump radiation, and supply a signal to the diode driver 117. Alternatively, the output from the photodetector can be provided to the

controller 626, which can control the drive current responsive thereto to insure that the desired optical pump power is supplied from the laser diode.

Reference is now made to Fig. 13, which is a system diagram of a communications laser installed in a wavelength division multiplexing (WDM) communication system. A laser source 701 including a coupled-cavity, optically-pumped solid state laser as described herein (e.g. with reference to Fig. 1) supplies optical radiation along the optical fiber 160 at an approximately constant predetermined power and wavelength. The optical radiation is modulated in an external modulator 711 with any suitable information signal, such as a cable TV signal, or a digital signal. The external modulator comprises any suitable form such as a Mach-Zender interferometer, an electro-absorption modulator, a waveguide, or a bulk modulator. External modulators are commercially available from Lucent Technologies of Breinigsville, Pennsylvania or Uniphase Telecommunications Products of San Jose, California. Using these external modulators, the laser output can be amplitude modulated, phase modulated, and/or frequency modulated for coherent communications, using techniques such as frequency shift keyed or phase shift keyed formats at multi-Gbit/second data rates.

Additional laser sources, such as laser sources 702 and 703 may also supply optical radiation at a constant, predetermined power and wavelength, although the wavelength may differ between the laser sources. These laser sources are respectively modulated in external modulators 712 and 713. Depending upon the embodiment, many additional laser sources may be utilized, each having a slightly different wavelength.

After being modulated by the external modulator 711, 712, and 713, the modulated optical signals are supplied to a multiplexer 720, such as a wavelength division multiplexer, which multiplexes the modulated optical signals into a single optical signal, so that they are transmitted along a single optical fiber 730. In an alternative embodiment without the multiplexer 720, a single modulated signal, such as the modulated optical signal from the first laser source, may be transmitted by itself along the optical fiber 730.

Generally, relatively short runs of optical fiber will not require amplification. For example, if a 100 mW laser source is modulated by an external modulator that attenuates the signal by a factor of four, and a typical single mode fiber is used that attenuates the signal by 0.22 dB per kilometer, amplification of the modulated signal will not be required for optical fiber lengths less than 60 km, thereby eliminating the need for light amplification systems. However, for long runs of optical fiber, or if other transmission losses are present, it may become necessary to amplify the combined modulated optical signals in an optical amplifier 735 such as an erbium-doped amplifier commercially available from Lucent Technologies of Breinigsville, Pennsylvania or Uniphase Telecommunications Products of San Jose, California.

When the multiplexed optical signals arrive at the receiving end, they are de-multiplexed into their respective wavelengths in a de-multiplexer 740, and then each of the individual modulated optical signals is individually demodulated in receiver/demodulators 741, 742 and 743 to provide the respective signals. After demodulation, the demodulated signals are then supplied by any suitable means to their respective end users for their intended uses such as watching television.

It will be appreciated by those skilled in the art that alternative embodiments may be implemented without deviating from the spirit or scope of the invention. For example, one or more additional components such as a light modulator and/or a polarizer can be situated on the optical base. Various suitable materials and methods can be utilized to hold the laser components to the base, including various adhesives and mechanical fasteners. This invention is to be limited only by the following claims, which include all such embodiments and modifications when viewed in conjunction with the above specification and accompanying drawings.

CLAIMS

WHAT IS CLAIMED IS:

1. A coupled-cavity laser that generates a polarized output, comprising:

a coupled cavity including a first end mirror, a second end mirror, and a partially reflective interface situated between said end mirrors, said coupled cavity defining a first cavity between said first end mirror and said partially reflective interface, and also defining a second cavity between said partially reflective interface and said second end mirror;

a gain medium situated within said first cavity;

an etalon situated within said second cavity, said etalon comprising a polarization selective material, said etalon having a thickness that selects a single lasing wavelength; and

an optical pump source for supplying optical pump radiation to the gain medium.

2. The laser of claim 1 wherein said gain medium has a gain bandwidth of larger than about 5 nm.

3. The laser of claim 2 wherein the gain medium comprises Er,Yb: glass.

4. The laser of claim 2 wherein the polarization selective etalon has a thickness within the range of 80 to 120 microns.

5. The laser of claim 1 wherein the partially reflective surface comprises a reflectivity within the range of about 15% to 25%.

6. The laser of claim 5 wherein the partially reflective surface comprises a reflectivity of about 20%..

7. The laser of claim 1 and further comprising an electro-optic modulator situated within said first cavity.

8. The laser of claim 7 and further comprising means for modulating the electro-optic modulator to shift the lasing wavelength at a predetermined rate.

9. The laser of claim 1 and further comprising a silicon base for mounting the source of optical pump radiation, the gain medium, and the polarization selective material.

10. The laser of claim 1 and further comprising a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the source of optical pump radiation to maintain an approximately

constant optical pump power.

11. The laser of claim 1 wherein said coupled cavity comprises a monolithic structure including said gain medium and said etalon.

12. A frequency-modulated coupled-cavity laser that generates a polarized output, comprising:

a coupled cavity including a first end mirror, a second end mirror, and a partially reflective interface situated between said end mirrors, said coupled cavity defining a first cavity between said first end mirror and said partially reflective interface, and a second cavity between said partially reflective interface and said second end mirror;

a gain medium and an electro-optic element situated within said first cavity;

a polarization selective element situated within said second cavity, said second cavity coupled to said first cavity; and

an optical pump source for supplying optical pump radiation to the gain medium.

13. The laser of claim 12 wherein the gain medium comprises Er,Yb: glass.

14. The laser of claim 12 wherein the partially reflective surface comprises a reflectivity within the range of about 15% to 25%.

15. The laser of claim 14 wherein the partially reflective surface comprises a reflectivity of about 20%.

16. The laser of claim 12, and further comprising means for modulating the electro-optic modulator to shift the lasing wavelength at a predetermined rate.

17. The laser of claim 12 and further comprising means for reducing relative intensity noise in the laser output.

18. The laser of claim 12 and further comprising a silicon base for mounting the source of optical pump radiation, the electro-optic material, the gain medium, and the polarization selective material.

19. The laser of claim 12 and further comprising a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the source of optical pump radiation to maintain an approximately constant optical pump power.

20. The laser of claim 12 wherein said coupled cavity comprises a monolithic structure including said electro-optic element, said gain medium, and said etalon.

21. A coupled-cavity laser that generates a polarized output, comprising:

a monolithic coupled cavity including a first end mirror, a second end mirror, and a partially reflective interface having a reflectivity between about 15% and 25% situated between said end mirrors, said coupled cavity defining a first cavity between said first end mirror and said partially reflective interface, and also defining a second cavity between said partially reflective interface and said second end mirror;

an electro-optic material and a gain medium situated within said first cavity, said gain medium having a gain bandwidth larger than about 5 nm;

an etalon comprising a polarization selective material situated within said second cavity, said etalon having a thickness that selects a single lasing wavelength; and

an optical pump source for supplying optical pump radiation to the gain medium.

22. The laser of claim 21 wherein said gain medium comprises Er,Yb: glass.

23. The laser of claim 21 wherein the polarization selective etalon has a thickness within the range of 80 to 120 microns.

24. The laser of claim 21 wherein the partially reflective surface comprises a reflectivity of about 20%.

25. The laser of claim 21 and further comprising means for modulating the electro-optic modulator to shift the lasing wavelength at a constant rate.

26. The laser of claim 21 and further comprising means for reducing relative intensity noise in the laser output.

27. The laser of claim 21 and further comprising a silicon base for mounting the source of optical pump radiation, the electro-optic material, the gain medium, and the polarization selective material.

28. The laser of claim 21 and further comprising a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the source of optical pump radiation to maintain an approximately constant predetermined pump power.

29. A coupled-cavity laser that generates a polarized output, comprising:

a monolithic coupled cavity including a first end mirror, a second end mirror, and a partially reflective interface having a reflectivity between about 15% and 25% situated between said end mirrors, said coupled cavity defining a first cavity between said first end mirror and said partially reflective interface, and also defining a second cavity between said partially reflective interface and said second end mirror;

an electro-optic material and a gain medium situated within said first cavity, said gain medium comprising Er,Yb: glass;

an etalon comprising a polarization-selective material situated within said second cavity, said etalon having a thickness that selects a single lasing wavelength;

a laser diode for supplying optical pump radiation to the gain medium;

a noise reduction system including

a photodetector situated to detect the intensity of the laser output from the coupled cavity, and

a noise reduction circuit that controls the laser diode to reduce relative intensity noise in the laser output; and

a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the source of optical pump radiation to maintain an approximately constant predetermined optical pump power.

30. The laser of claim 29 wherein the polarization selective etalon has a thickness within the range of 80 to 120 microns.

31. The laser of claim 30 wherein the polarization selective etalon has a thickness of about 100 microns.

32. The laser of claim 29 wherein the partially reflective surface comprises a reflectivity of about 20%.

33. The laser of claim 29 and further comprising an electrical circuit for modulating the electro-optic modulator to shift the lasing wavelength at a constant rate.

34. The laser of claim 29 and further comprising a silicon base for mounting the source of optical pump radiation, the electro-optic material, the gain medium, and the polarization selective material.35. The laser of claim 34 and further comprising means for maintaining an approximately constant first temperature in said gain medium and an approximately constant second, different temperature in said laser diode.

36. The laser of claim 35 and further comprising a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the source of optical pump radiation to maintain an

approximately constant temperature in said gain medium.

37. A method of forming a coupled cavity laser to provide a selected lasing wavelength, comprising the steps of:

providing a solid state gain medium that has a gain bandwidth;

providing an electro-optic material;

selecting an etalon comprising a polarization selective material having a thickness that selects a lasing wavelength;

forming a partially reflective interface between the etalon and the gain medium;

coupling the electro-optic material, the gain medium, and the etalon to form a monolithic structure;

forming end mirrors on said monolithic structure to provide a monolithic wavelength-selective coupled cavity; and

situating a pump source in a position to optically pump said gain medium.

38. The method of claim 37 and further comprising the step of situating a fiber optic coupling assembly in a position to couple the output of the coupled cavity laser into an optical fiber.

39. The method of claim 37 and further comprising the step of mounting said monolithic coupled cavity and said pump source on a silicon base.

40. The method of claim 39, and further comprising the step of mounting a fiber optic coupling assembly on the silicon base in a position to couple the output of the coupled cavity laser into a fiber optic cable..

41. The method of claim 37 wherein the partially reflective coating is formed to provide a reflectivity within a range of about 15% to 25%.

42. A fiber optic communications system comprising:

a coupled-cavity, optically-pumped solid state laser that provides a laser beam at a predetermined wavelength, said coupled cavity laser including an intracavity frequency modulator;

a modulator situated to receive said laser beam, said modulator modulating said laser beam with an information signal; and

an optical fiber for transmitting the modulated laser radiation.

43. The communications system of claim 42 wherein said coupled-cavity laser further comprises a noise reduction system for reducing relative intensity noise.

44. The communications system of claim 42 wherein the coupled-cavity laser comprises a gain medium including Er,Yb: glass.

45. The communications system of claim 42, wherein said intracavity modulator comprises means for modulating the laser output to reduce stimulated Brillouin scattering effects in said optical fiber.

46. The communications system of claim 42, wherein said intracavity modulator comprises means for modulating the laser output to shift the lasing wavelength by a predetermined frequency at a constant rate.

47. The communications system of claim 42, wherein said coupled-cavity laser further comprises:

a laser diode to supply optical pump radiation; and

means for maintaining an approximately constant laser output power, including a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the laser diode to maintain an approximately constant pump power.

48. The communications system of claim 42, and further comprising a receiver/demodulator coupled to the optical fiber to receive and demodulate the modulated laser beam.

49. A wavelength division multiplexed (WDM) fiber optic communications system comprising:

a plurality of coupled-cavity, optically-pumped solid state lasers, each of which provides a laser beam at a predetermined wavelength different from other of said plurality of lasers, each of said coupled cavity lasers including an intracavity frequency modulator;

a plurality of modulators situated to receive, respectively, said laser beams, each of said modulators modulating its respective laser beam with an information signal;

a plurality of optical fibers for transmitting the modulated laser radiation;

a wavelength division multiplexer for receiving said plurality of optical fibers and modulating them onto a single optical fiber

50. The communications system of claim 49 wherein each of said plurality of coupled-cavity lasers further comprises a noise reduction system for reducing relative intensity noise.

51. The communications system of claim 49 wherein at least one of said plurality of coupled-cavity lasers comprises a gain medium including Er,Yb: glass.

52. The communications system of claim 49, wherein said intracavity modulators comprise means for modulating their respective laser outputs to reduce stimulated Brillouin scattering effects in said optical fibers.

53. The communications system of claim 49, wherein said intracavity modulators comprise means for modulating their respective laser outputs to shift the lasing wavelength by a predetermined frequency at a constant rate.

54. The communications system of claim 49, wherein said coupled-cavity laser further comprises:

a laser diode to supply optical pump radiation; and

means for maintaining an approximately constant laser output power, including a photodetector for sensing the optical pump radiation and a circuit responsive thereto for controlling the laser diode to maintain an approximately constant pump power.

55. The communications system of claim 49, wherein said intracavity modulator comprises means for modulating the laser output to reduce stimulated Brillouin scattering effect in said optical fiber.

56. The communications system of claim 49, and further comprising a receiver/demodulator coupled to the optical fiber to receive and demodulate the modulated laser beam.

57. A method of transmitting an information signal over an optical fiber comprising the steps of:

providing a coupled-cavity, optically-pumped solid state laser that has a predetermined lasing wavelength;

frequency modulating said coupled-cavity laser in an intracavity modulator so that the laser output from said coupled-cavity laser is modulated at a predetermined rate;

modulating said laser output with said information signal; and

transmitting the modulated laser radiation over an optical fiber.

58. The method of claim 57 and further comprising the step of controlling said coupled-cavity laser to reduce relative intensity noise.

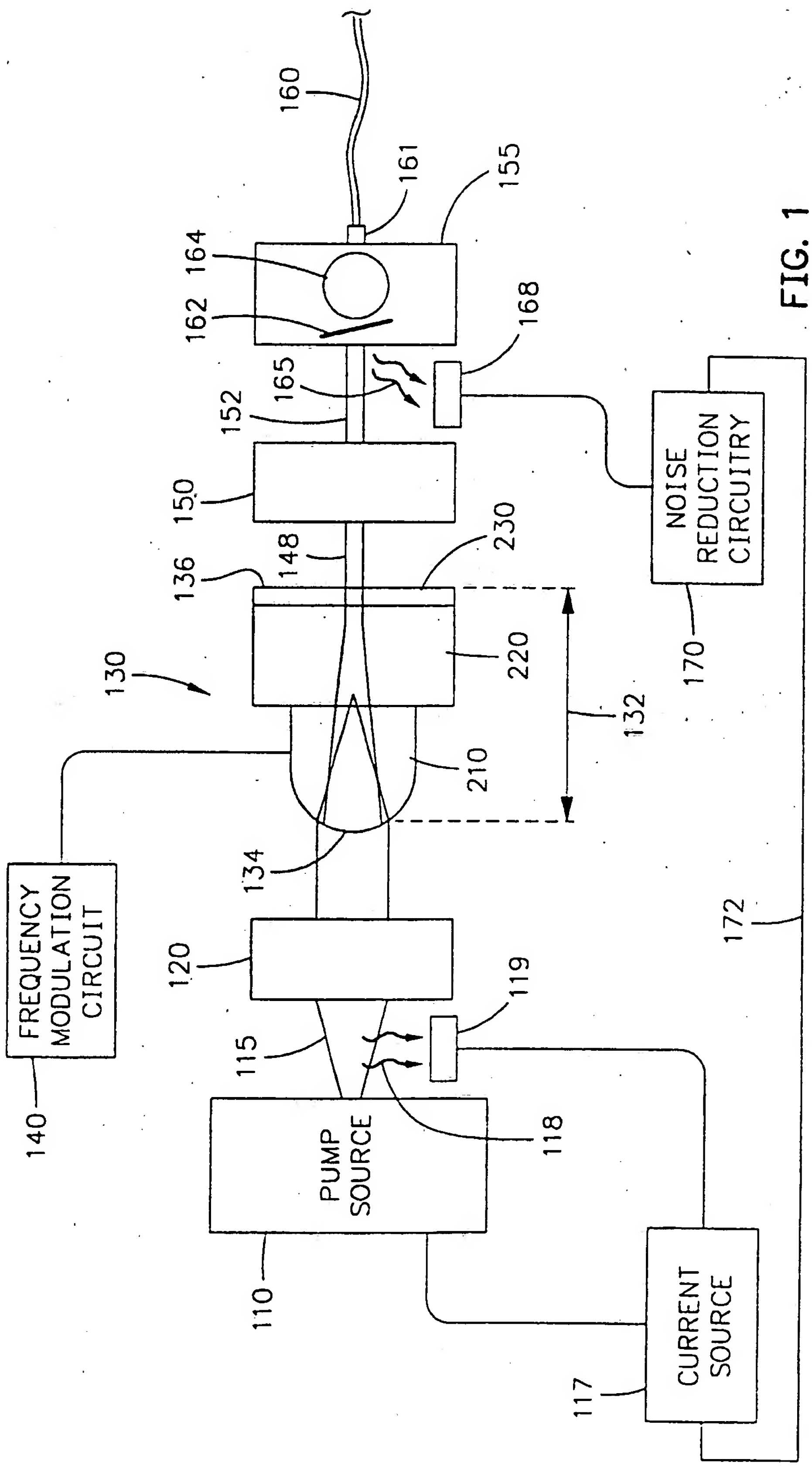
59. The method of claim 57, wherein said step of frequency modulating the laser includes modulating the lasing frequency to reduce stimulated Brillouin scattering effects in said optical fiber.

60. The method of claim 57, wherein said step of intracavity modulation comprises shifting the lasing wavelength by a predetermined frequency at a constant rate.

61. The method of claim 57, wherein said coupled-cavity laser further comprises a laser diode to supply optical pump radiation and a photodetector for sensing the power of the optical pump radiation, and further comprising the step of maintaining an approximately constant power laser output from said coupled-cavity laser by controlling the laser diode to maintain an approximately constant pump power.

62. The method of claim 57, and further comprising the step of receiving said modulated laser beam from said optical fiber and demodulating it to receive the information signal.

63: The method of claim 57 and further comprising the step of multiplexing at least one additional modulated laser output to said first modulated laser output to provide a multiplexed optical signal, and transmitting said multiplexed optical signal over an optical fiber.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148
136
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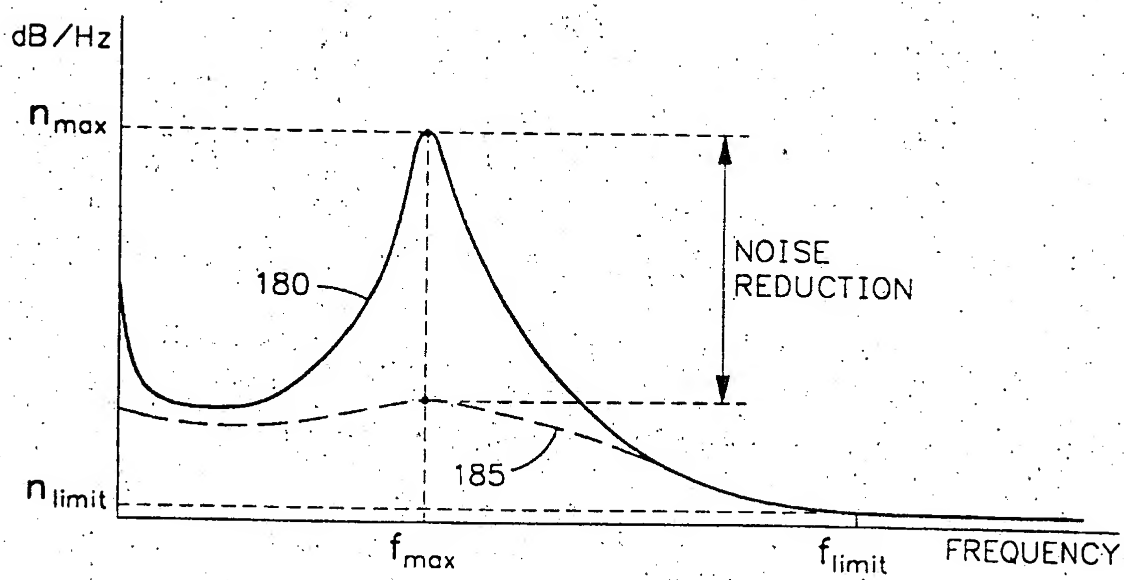
130
220
132
210
134
120
119
115
118
110
117
140
170
172
FREQUENCY MODULATION CIRCUIT
PUMP SOURCE
CURRENT SOURCE
NOISE REDUCTION CIRCUITRY

FIG. 1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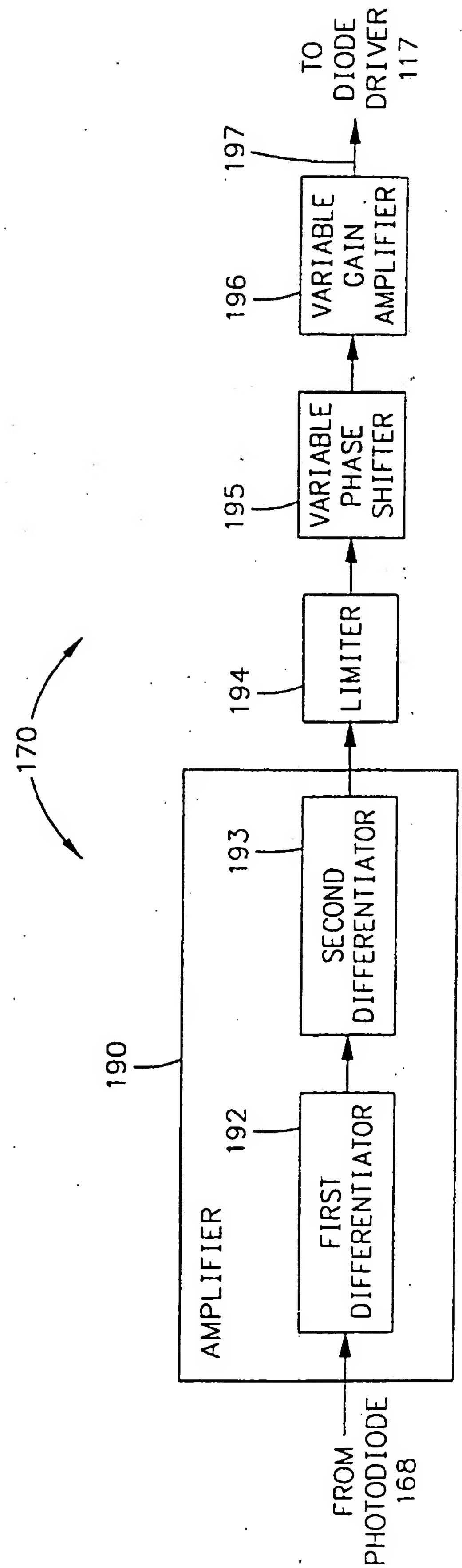
NOISE
REDUCTION
180
185
n_{limit}
f_{max}
f_{limit}
FREQUENCY

FIG. 2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DRIVER
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GAIN
AMPLIFIER
196
VARIABLE
PHASE
SHIFTER
195
LIMITER
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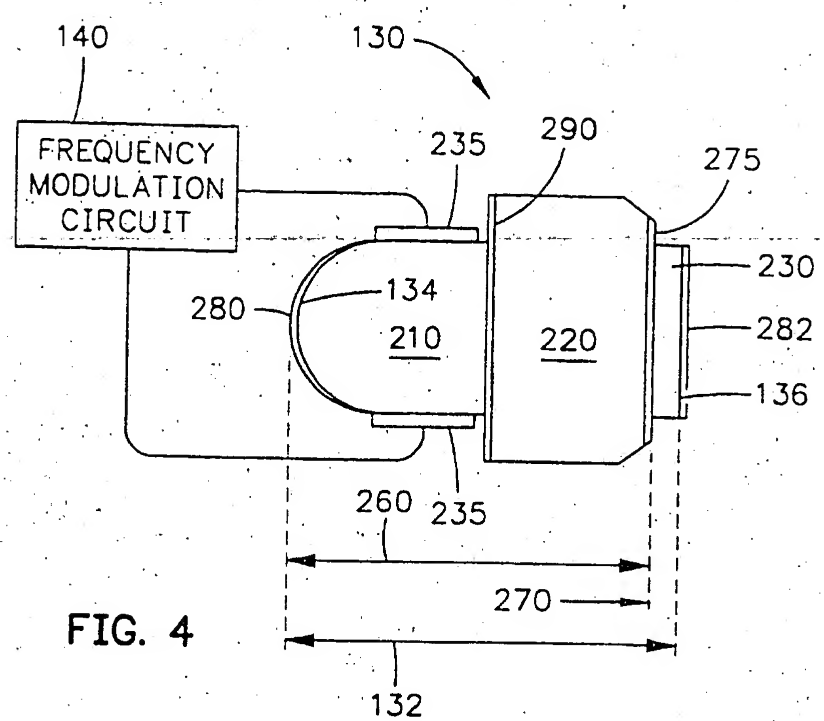
170
SECOND
DIFFERENTIATOR
193
190
FIRST
DIFFERENTIATOR
192
AMPLIFIER
FROM
PHOTODIODE
168

FIG. 3


140
130
FREQUENCY
MODULATION
CIRCUIT
235
290
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134
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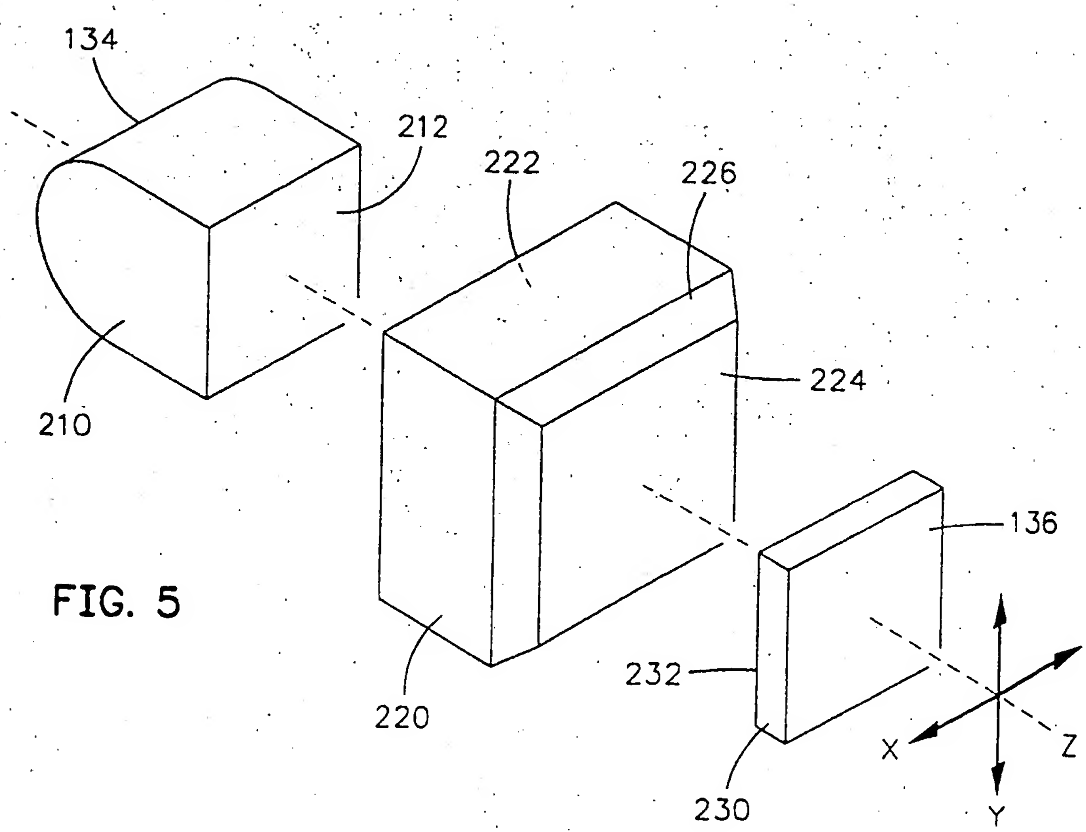
235
270
132

FIG. 4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226
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220
232
230
X
Y
Z

FIG. 5

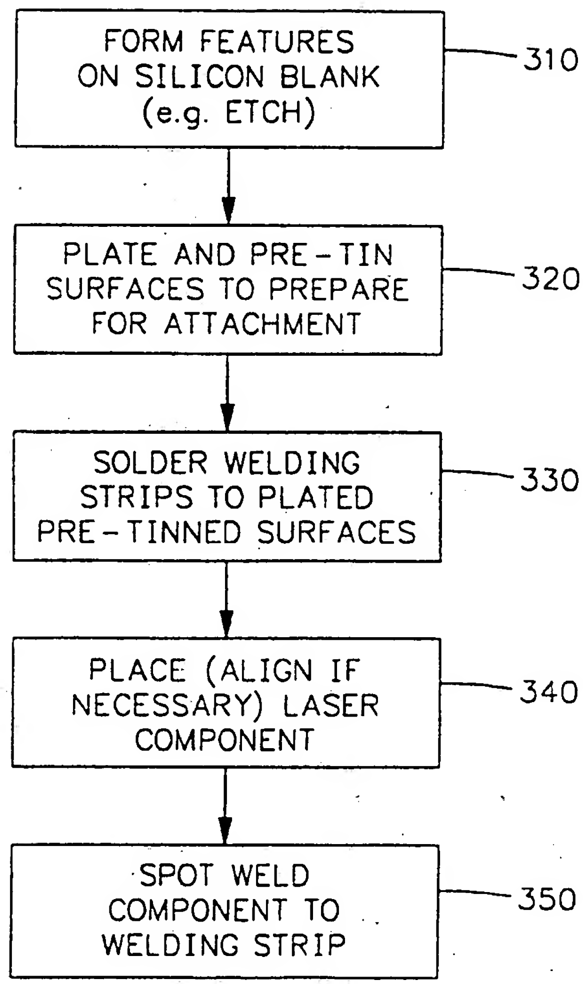
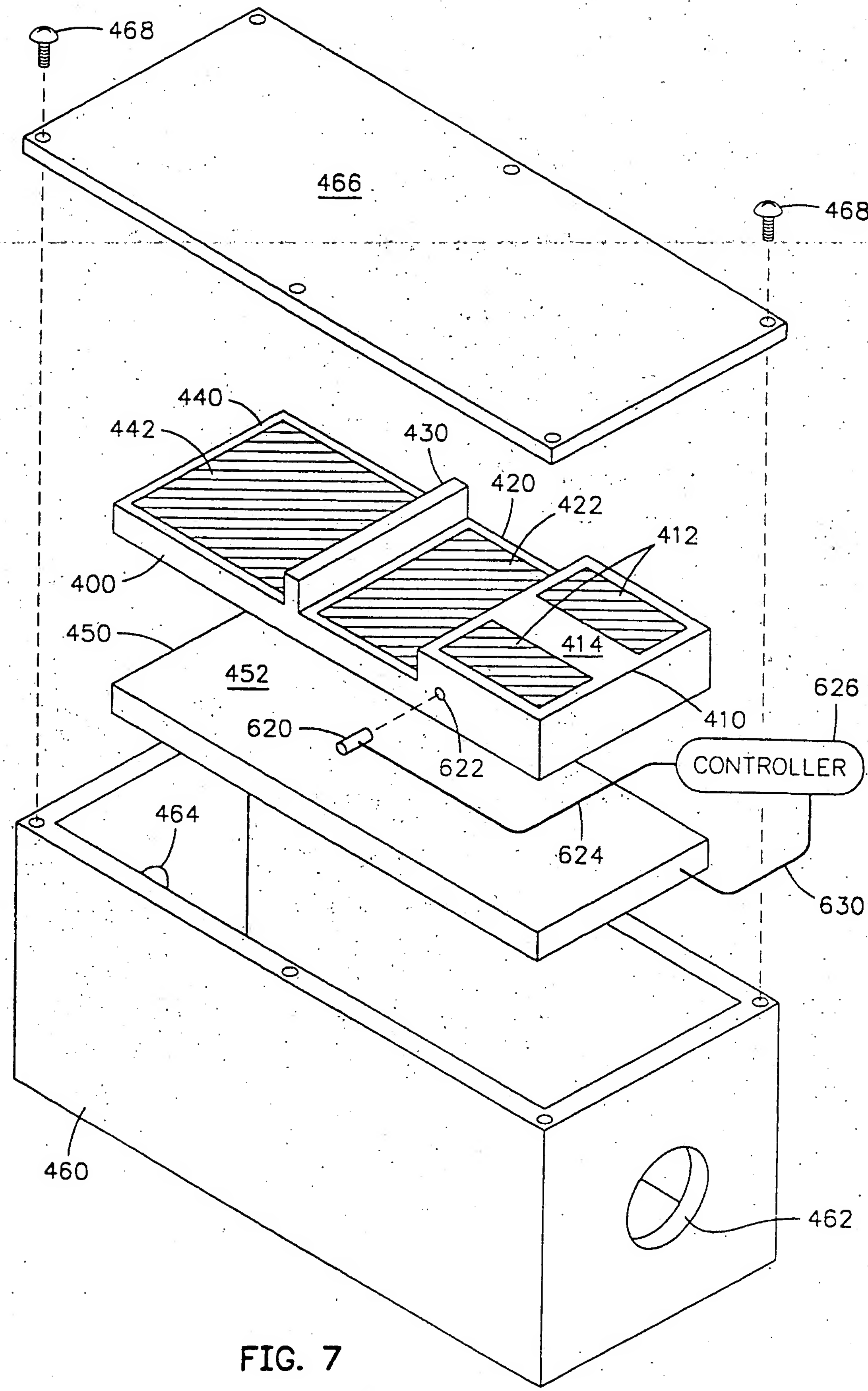

FORM FEATURES ON SILICON BLANK (e.g. ETCH)
310
PLATE AND PRE-TIN SURFACES TO PREPARE FOR ATTACHMENT
320
SOLDER WELDING STRIPS TO PLATED PRE-TINNED SURFACES
330
PLACE (ALIGN IF NECESSARY) LASER COMPONENT
340
SPOT WELD COMPONENT TO WELDING STRIP
350

FIG. 6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CONTROLLER
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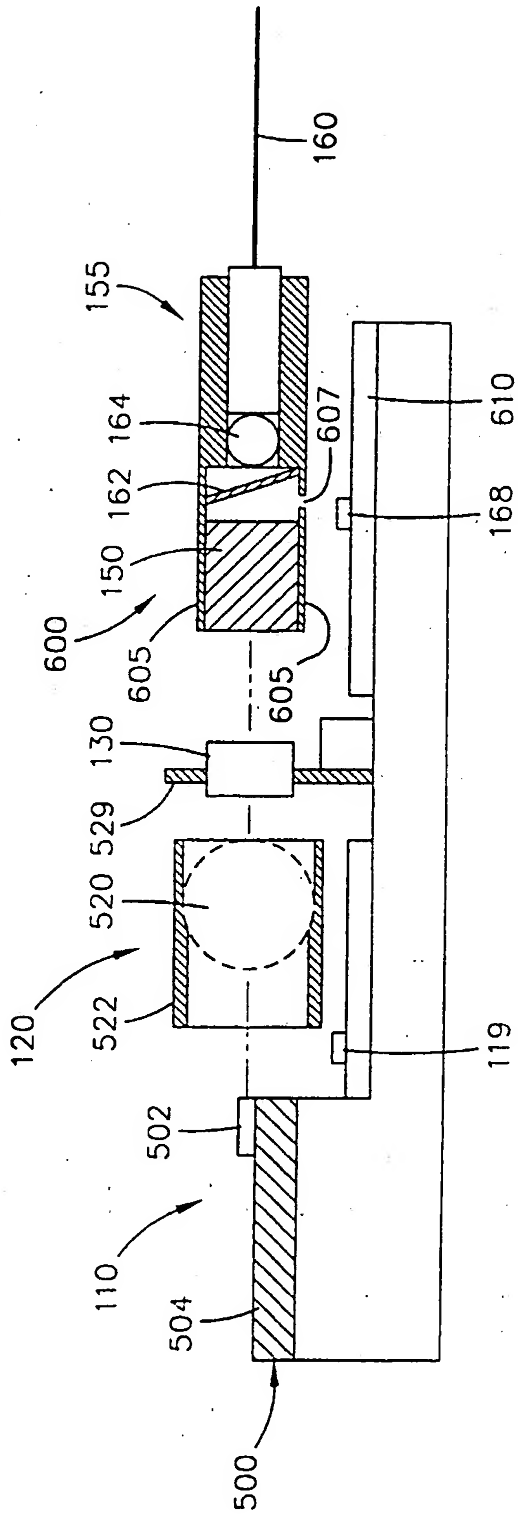
624
630
460
462

FIG. 7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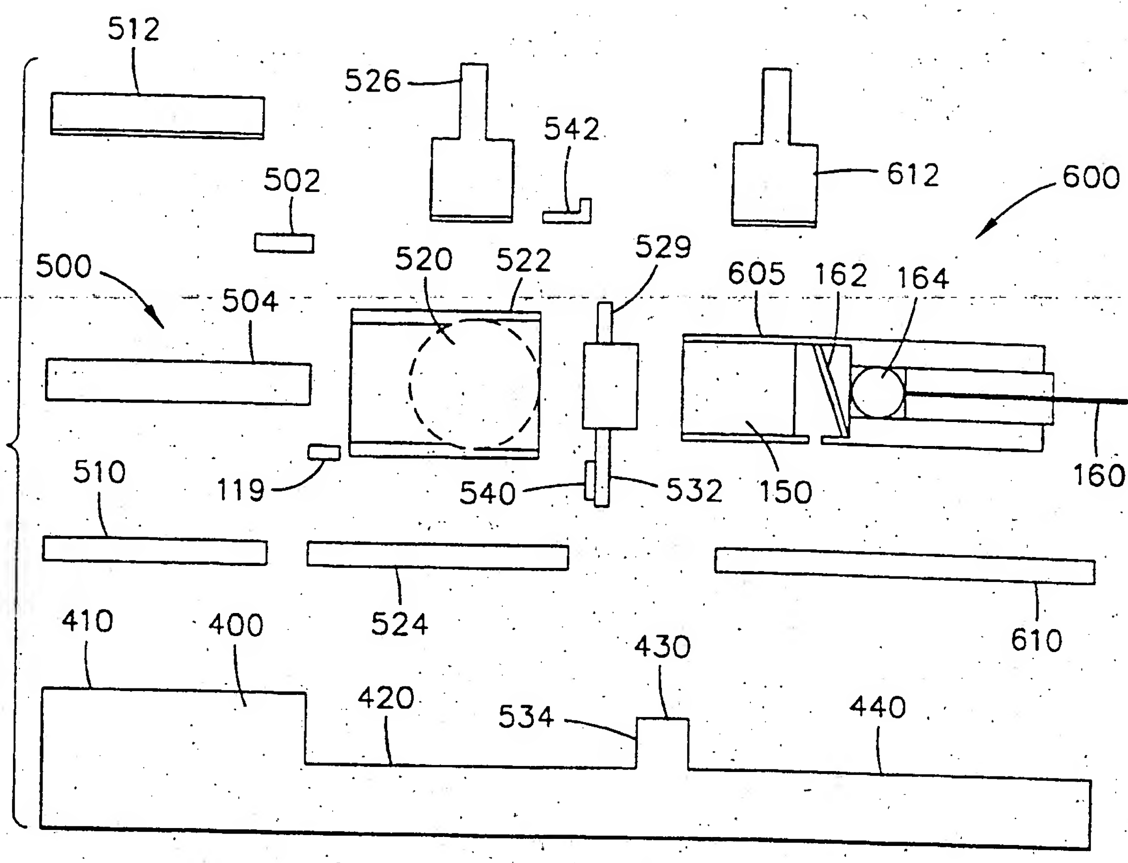
502
110
504
500

FIG. 8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526
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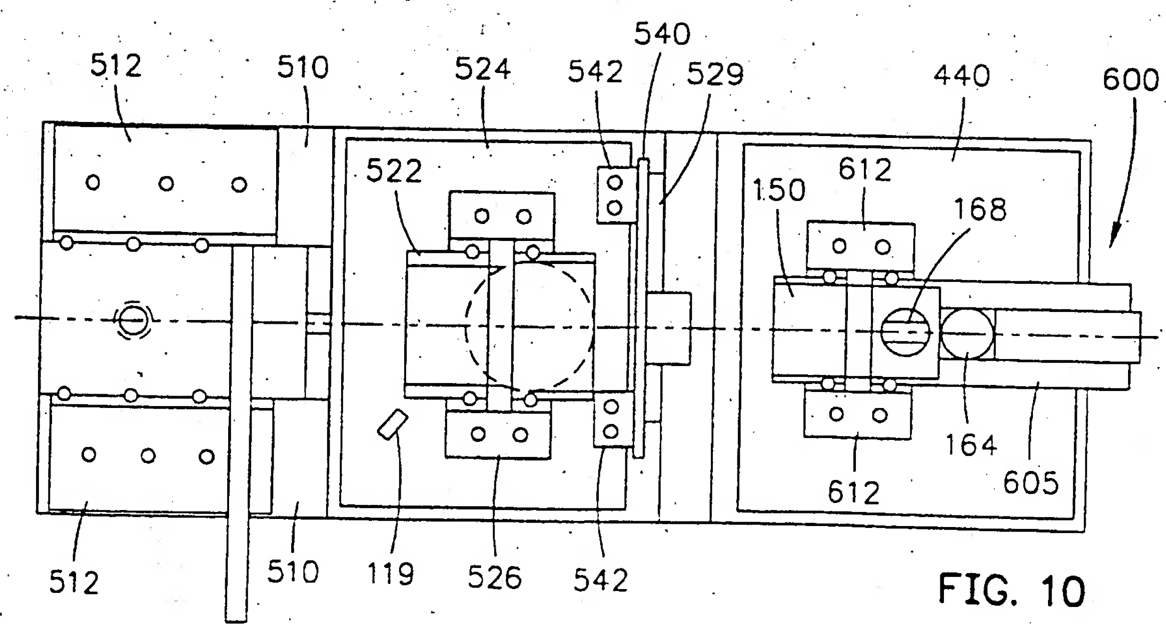
610
410
400
420
534
430
440

FIG. 9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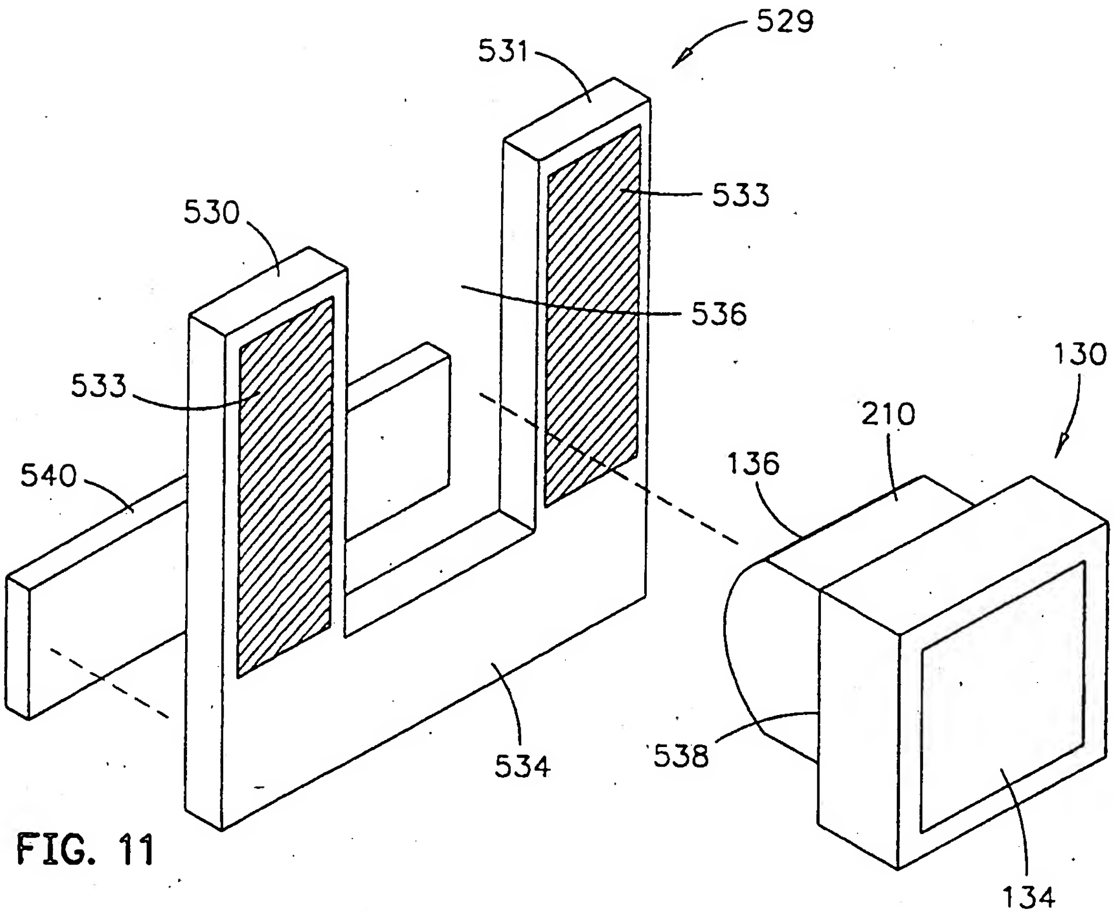
119
526
542

FIG. 10


529
531
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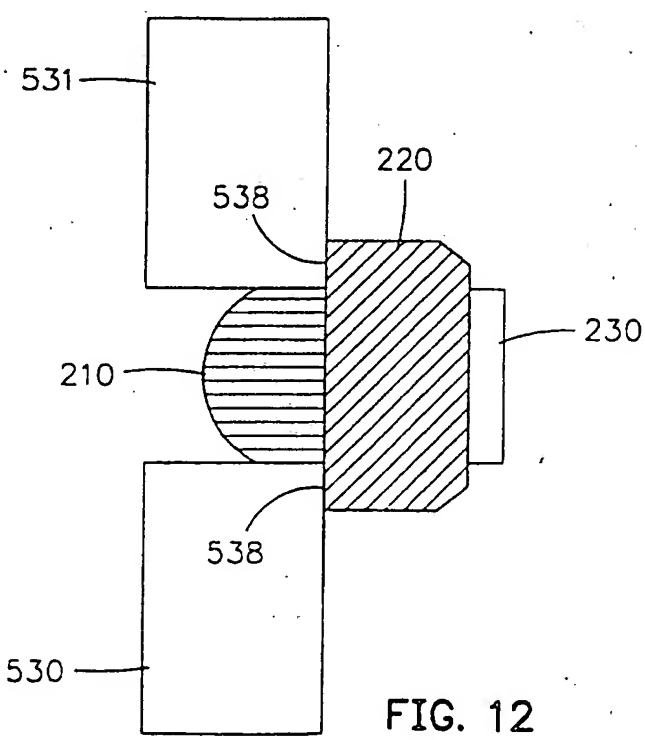
533
210
540
136
538
534
134

FIG. 11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538
230
210
538
530

FIG. 12

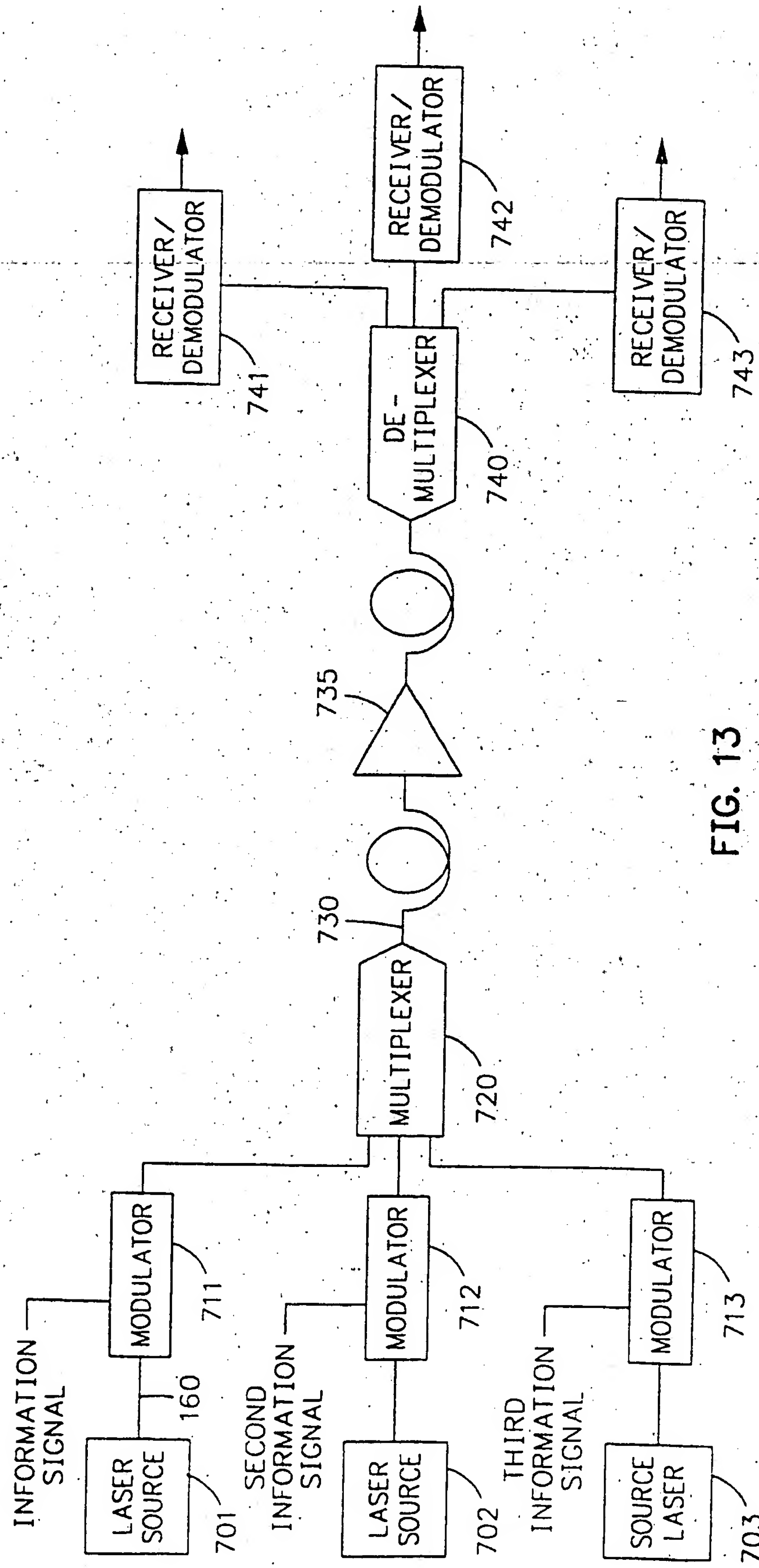
INFORMATION SIGNAL
LASER SOURCE
701
160
MODULATOR
711
SECOND INFORMATION SIGNAL
LASER SOURCE
702
MODULATOR
712
THIRD INFORMATION SIGNAL
SOURCE LASER
703
MODULATOR
713
MULTIPLEXER
720
730
735
DE-MULTIPLEXER
740
RECEIVER/ DEMODULATOR
741
RECEIVER/ DEMODULATOR
742
RECEIVER/ DEMODULATOR
743

FIG. 13

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/04814

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/082 H01S3/098 H04B10/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	TACCHEO S ET AL: "LINEARLY POLARIZED, SINGLE-FREQUENCY, WIDELY TUNABLE ER:YB BULK LASER AT AROUND 1550 NM WAVELENGTH" APPLIED PHYSICS LETTERS, vol. 69, no. 21, 18 November 1996, pages 3128-3130, XP000643597 see page 3128, right-hand column, line 24 - page 3129, left-hand column, line 21 see page 3130, column 2, line 3 - line 16 ---	1-63
Y	ITOH T ET AL: "Q-SWITCHING AND MODE SELECTION OF COUPLED-CAVITY ER, YB:GLASS LASERS" JAPANESE JOURNAL OF APPLIED PHYSICS, vol. 36, no. 2B, 15 February 1997, pages L206-L208, XP000733111 see figure 1 ---	1-63

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 June 1999	05/07/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Galanti, M

1

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	US 5 265 113 A (HALLDOERSSON THORSTEINN ET AL) 23 November 1993 see column 2, line 45 - line 56	9,10,18, 19,27, 28, 34-36, 39,40, 47,54,61
Y	US 5 341 393 A (HYUGA HIROAKI ET AL) 23 August 1994 see figure 3	11,20
Y	US 5 381 431 A (ZAYHOWSKI JOHN J) 10 January 1995 see abstract	20
Y	EP 0 331 338 A (AMERICAN TELEPHONE & TELEGRAPH) 6 September 1989 see abstract; figure 1	38-40
Y	TACCHEO S ET AL: "INTENSITY NOISE REDUCTION IN A SINGLE-FREQUENCY YTTERBIUM-CODOPED ERBIUM LASER" OPTICS LETTERS, vol. 21, no. 21, 1 November 1996, pages 1747-1749, XP000632493 cited in the application see abstract	17,26, 43,50,58
Y	EP 0 812 078 A (FUJITSU LTD) 10 December 1997 see figure 1	49

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern: al Application No
PCT/US 99/04814

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		DE 68918133 D	20-10-1994
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